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‘Can Simple Biological Systems be Built from Standardized Interchangeable Parts?’ Negotiating Biology and Engineering in a Synthetic Biology Competition

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Abstract
Synthetic biology represents a recent attempt to bring engineering principles and practices to working with biology. In practice, the nature of the relationship between engineering and biology in synthetic biology is a subject of ongoing debate. The disciplines of biology and engineering are typically seen to involve different ways of knowing and doing, and to embody different assumptions and objectives. Tensions between these approaches are playing out as the field of synthetic biology is being established. Here we study negotiations between engineering and biology through the International Genetically Engineered Machine (iGEM) competition. This undergraduate competition has been important in launching and bootstrapping the field of synthetic biology, and serves as a test-bed for the engineering approach. We show how a number of issues that iGEM teams must grapple with - including standardization, design, intellectual property, and the imagination of the social - involve the negotiation of engineering, biology, and other disciplines (including computer science), in ways more complex than the engineering rhetoric of synthetic biology implies. We suggest that a new moral economy for synthetic biology is being created, in which epistemic and institutional values, conventions and practices are being negotiated and (re)defined.

Keywords: design; human practices; intellectual property; interdisciplinarity; standards; synthetic biology

Introduction

Synthetic biology is an approach to biological engineering that has been receiving increased attention and funding over the past 10-15 years. Several types of research activities are routinely cast under the heading of synthetic biology.[1] The strand that has arguably grown fastest and received most attention over the past decade centres around trying to design and build biological systems using standardized genetic sequences. This ‘parts-based’ approach was initially advanced by a small cohort of researchers in the US with backgrounds in engineering disciplines (including civil and software engineering). One of their more widely cited definitions emphasizes two core objectives: “the design and construction of new biological parts, devices, and systems,” and “the re-design of

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[1] O’Malley et al, “Knowledge-Making Distinctions,” 2008.

existing, natural biological systems for useful purposes."[2] An early focus of this parts-based approach has been to develop genetic components (the best-known of which are called 'BioBrick™ standard biological parts') that can, in theory, be combined (as one might assemble Lego® bricks) to build biological devices that perform specific functions.[3]

Early advocates from the engineering community have made a point of distinguishing synthetic biology from genetic engineering. They argue that 'genetic *engineering*' is a misnomer, and that since its emergence over the past 30-40 years such work has typically been more of an artisanal craft than a true engineering discipline.[4] In contrast, synthetic biology aspires towards 'real' engineering with biology, and emphasizes practices such as standardization, decoupling of design and fabrication, scaling up, and industrialization for the development of biologically-based products and processes. Its proponents position synthetic biology as an explicit and innovative attempt to import such concepts and practices from engineering to biology. This agenda is expressed in the titles of research commentaries such as 'Foundations for engineering biology,'[5] and 'Synthetic biology – putting engineering into biology.'[6] It also emerges in the stated aim of the US Synthetic Biology Engineering Research Center (SynBERC), 'to catalyze biology as an engineering discipline.'[7]

In this rhetorical presentation of synthetic biology, biology is typically described as concerned with discovery-based research that attempts to better understand the natural world, while the focus of engineering is portrayed as application-oriented and concerned with making (new) things. This broad difference in the purpose or end goals of science and engineering has been noted by Vincenti,[8] and carries through into caricatures commonly offered at synthetic biology conferences and meetings. We often hear aphorisms such as 'A Scientist discovers that which exists. An Engineer creates that which never was.'[9] In a similar vein, the following vignette is routinely told by Tom Knight, an early proponent of synthetic biology based at the Massachusetts Institute of Technology (MIT):

> The biologist goes into the lab in the morning, does an experiment, discovers that the system she's looking at is twice as complicated as she thought it was, and says

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[2] Synthetic Biology, "Synthetic biology is," 2012.

[3] The DNA sequence of a biological part/BioBrick might encode a specific gene, or it might code for a smaller functional genetic element such as a promoter or terminator sequence, a ribosome binding site, etc.

[4] The comedian Simon Munnery is sometimes quoted to highlight this: "What genetic engineers do [today] isn't really engineering. The engineering equivalent of what genetic engineers do is to throw a load of steel and concrete into a river, and then if someone manages to walk across it, call it a bridge" (Munnery, "New World Order," 2008.)

[5] Endy, "Foundations for Engineering Biology," 2005.

[6] Heinemann and Panke, "Synthetic Biology," 2006.

[7] http://www.synberc.org/. Accessed June 3, 2012.

[8] Vincenti, *What Engineers Know*, 1990. For a detailed treatment of this topic, see also Schyfter, "Propellers and Promoters," 2013.

[9] Theodore von Karman, quoted in Knight, "Engineering Novel Life," 2005.

> 'Great, I get to write a paper.' The engineer goes into the laboratory, does the same experiment, gets the same result, and says 'Darn! How do I get rid of that?'[10,11]

A central challenge articulated for synthetic biology is how to bring engineering principles and practices to bear when working with living organisms and biological materials – with 'the stuff of life.' Early advocates regularly highlight previous engineering successes when proposing how and why biology is an important new substrate for engineering, arguing, for example, that "Our planes and computer processors are made possible by sophisticated engineering programs that model characterized parts that are designed and manufactured to work together predictably," and concluding that "it is economically and socially important that we improve the efficiency, reliability and predictability of our biological designs."[12] The idea of 'decoupling' the design of biological systems from their fabrication (analogous to the decoupling of chip design from material fabrication of integrated circuits) is central to synthetic biology, and re-orients traditional biotechnology and genetic engineering away from their primary focus on the biology of the systems being engineered.

This brief introduction highlights broad caricatures used by a small number of engineering researchers to frame parts-based approaches to synthetic biology. In general terms, they cast engineering as a more systematic, rational, and application-oriented discipline than biology. These characteristics are advanced self-consciously as a means of proposing a new agenda for research and industrial development, asserting the distinctiveness of synthetic biology, justifying its potential, and securing support for the field. This agenda is not infrequently met with scepticism by researchers trained in more biologically grounded disciplines (perhaps because they interpret engineering principles to be more rigid than they may actually be): "The idea of standard biological componentry is either dismissed as a research question because [people think] it's irrelevant or dismissed as a research question because [they believe] it's impossible."[13] As institutions and research agendas, and values and conventions for synthetic biology are being established, such questions are being tested in practice. The negotiation of engineering and biology in the making of this discipline is a rich topic for study by researchers in science, technology and engineering studies.

In this paper we explore how the relationship between engineering and biology is being carved out in practice in synthetic biology. The site we focus on is the International Genetically Engineered Machine competition (iGEM). iGEM is an annual competition in which teams of university students from around the world use synthetic biology to design and build an engineered organism that performs a function of their choosing. Although just one of several synthetic biology initiatives underway, iGEM has proven to be important in many respects. It has been a key vehicle for training and community

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[10] Knight, "An interview," 2008.

[11] Although many engineers acknowledge the irreducible complexity of the systems they work on, those articulating the agenda for synthetic biology state a particular concern with managing the complexity and seeming unruliness of living systems.

[12] Arkin, "Setting the Standard," 2008, p.774.

[13] Drew Endy, quoted in Katsnelson, "Brick by Brick," 2009, p.42.

formation in synthetic biology, enrolling students, advisors and laboratories across the globe into a common project with shared norms. iGEM is also making material contributions to developing technical infrastructure and defining a research programme for parts-based synthetic biology.

Framed by the early proponents of synthetic biology as an engineering competition — that is, a competition focused primarily on designing and making things — iGEM brings together students from a variety of disciplines to work on a team project. This confluence of disciplines complicates ethnographic analyses of the sort undertaken by Knorr-Cetina,[14] in which physicists and molecular biologists were studied as practitioners working in distinct sites and laboratories. Here we encounter a situation in which scientists and engineers still in-the-making are being brought together for the purposes of developing a team project. The agenda of parts-based synthetic biology has been set out for them, along with a host of competition rules for them to follow. iGEM students are not in a position to alter these parameters significantly or challenge the broad rhetoric and caricatures of the field. But following how these teams negotiate the competition's demands and create their own discourses, practices, and divisions of labour to develop a workable project provides insights regarding the ways in which the relationship between engineering and biology is evolving in practice, and how the identities of synthetic biology and synthetic biologists are being formed through this process. In studying iGEM, we show how the relationships between biology, engineering and other disciplines are more complicated and nuanced than caricatures of synthetic biology would suggest. Students have to negotiate the demands of both biology and engineering throughout the competition, and in practice it seems that biology is not easily made subservient to the goals of engineering. Rather than witnessing the imposition of one epistemic culture on another, we suggest that a new 'moral economy' is being forged, in which values, conventions, and ways of knowing, doing and sharing are being negotiated and (re)defined.[15] This offers interesting possibilities for study and intervention by scholars from both science studies and engineering studies.

Our analysis draws on participant-observation and ethnographic engagement with the iGEM competition over the past four years. The University of Edinburgh has supported an iGEM team every year since 2006, and we have been involved as advisors to this team since 2008, focusing in particular on the 'Human Practices' dimension of the iGEM competition (see below). In 2008, our interactions with the team consisted of leading a single discussion session with the students, but in subsequent years we have become increasingly involved in an advisory capacity. During the summer of 2011 we met with the team approximately once a week to discuss both the scientific and social science aspects of their project.[16] We have also given presentations, led workshop activities, and offered feedback on an *ad hoc* basis to other iGEM teams in the UK and other parts of the world. In 2009 we attended the competition final (the iGEM Jamboree) at MIT in our capacity as advisors to the University of Edinburgh iGEM team, and we

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[14] Knorr-Cetina, *Epistemic Cultures*, 1999.

[15] McCray, "Large Telescopes," 2000; Atkinson-Grosjean and Fairley, "Moral Economies," 2009.

[16] Calvert did the same in 2012.

returned to the Jamboree in 2010 as Human Practices Judges. One of us (Calvert) was also a Human Practices Judge at the 2011 World Championship. In addition to our participant-observation of iGEM, we draw on documentary and online sources relating to synthetic biology and iGEM.

History, Objectives and Structure of iGEM

"Can simple biological systems be built from standardized interchangeable parts, or is biology so complex that each case is unique?"[17] The question that orients the iGEM competition is also the title of this paper. It reflects the focus of the iGEM competition on *making things*, and emphasizes the design challenge that lies at the heart of this engineering competition. To address this question, interdisciplinary teams of students are issued a set of materials in the form of standardized DNA sequences ('biological parts') from an open-source registry (the Registry of Standard Biological Parts, based at MIT),[18] and are asked to use these standard parts as a starting point for designing a genetic 'circuit' or 'device' of their choosing. The teams are given the summer months to design, test, and build their biological device.[19] The competition founders consciously decided to target undergraduates since, as Randy Rettberg, the director of iGEM puts it, "undergraduates don't know what you can't do."[20]

The teams then congregate at MIT in the autumn of every year to present their projects and compete for prizes. The projects are assessed by a cadre of volunteer judges, most of whom are academic advisors to iGEM teams (such as the authors of this paper), but also typically include judges from the biotech industry as well as funding and government agencies. Project assessment is based on an oral presentation, a poster session, and evaluation of the team's wiki page. Each team is eligible to win a medal (bronze, silver or gold) based on their performance. 'Track prizes' are awarded for the winning project in a number of application areas, and special prizes are also given out (including a 'Human Practices' prize). The Grand BioBrick Trophy is awarded to the team with the best overall project.

The projects undertaken by iGEM teams vary widely in scope and application, and include medical, environmental, agricultural, industrial, and even extraterrestrial applications, as well as what might be thought of as more 'basic' scientific projects. To provide a few examples, the 2007 University of California, Berkeley iGEM team attempted to develop a synthetic blood substitute;[21] the 2009 University of Cambridge team (winners of the BioBrick trophy that year) engineered *E. coli* to synthesize coloured pigments visible to the naked eye;[22] the 2010 team from the University of Bristol produced bacterial capsules that detect the presence of nitrates in soil (to assist with more

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[17] Rettberg, "iGEM," 2009.
[18] Registry of Standard Biological Parts, 2013.
[19] Formally, students are meant to work for 10 weeks over the summer, but in practice many teams start earlier and work until just before the competition finals in October/November.
[20] Rettberg, "iGEM," 2009, p.27.
[21] Berkeley iGEM Team, 2007.
[22] Cambridge iGEM Team, 2009.

efficient fertilizer application);[23] and the 2010 team from Valencia engineered yeast to produce a dark pigment with the aim of raising the temperature of Mars, as a first step towards terraforming the planet.[24]

iGEM originated as a class offered at MIT during the Independent Activities Period in 2003. In 2004 it broadened out to a small number of US universities, and in 2005 two European teams joined the competition.[25] Since then it has grown exponentially; the 2012 competition involved 191 teams from around the world, including 83 teams from the Americas, 53 teams from Europe, and 55 teams from Asia.[26] The development of iGEM as a competition was influenced by early conversations with Lynn Conway, a pioneer of very large scale integrated (VLSI) electronics courses.[27] It was also inspired by the FIRST Robotics high school competition, which started in 1992 and by 2009 had 1700 teams with a budget of around $30 million.[28] Such competitions are not unusual in computer science and engineering – rockets, robots, and solar and electric cars are the focal points of several student competitions – but they are less common in the biological sciences.

iGEM has introduced synthetic biology to a wide range of participants, including undergraduate and graduate students, as well as some high school students.[29] A number of iGEM participants have gone on to pursue further work in synthetic biology.[30] Some projects initiated by iGEM teams have become the basis for more formally funded university research projects. For example, the 2006 University of Edinburgh team developed a proof-of-principle bacterial biosensor for detecting arsenic in drinking water, which has subsequently led to publications[31] and the awarding of research grants to develop this work. Several of the research projects currently underway at the Centre for Synthetic Biology and Innovation at Imperial College London originated as iGEM projects that have successfully obtained funding from organizations including the Gates Foundation. The recent plethora of policy reports about synthetic biology also regularly mention iGEM as an important part of this emerging technology.[32]

Negotiating Engineering and Biology through iGEM

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[23] Bristol iGEM Team, 2010.
[24] Valencia iGEM Team, 2010.
[25] Brown, “The iGEM Competition,” 2007
[26] To cope with the growing number of teams, the 2011 competition structure changed from hosting a single Jamboree at MIT in November to holding ‘regional’ finals in October (in Europe, North America and Asia), from which approximately the top 30% of teams were invited to the ‘World Championship’ Jamboree at MIT.
[27] Smolke, “Building Outside of the Box,” 2009.
[28] Rettberg, “iGEM,” 2009.
[29] A high school division of iGEM was launched in 2011, see http://igem.org/High_School_Division
[30] Mitchell et al, “Experiential Engineering,” 2011.
[31] For example, de Mora et al, “A pH-based Biosensor,” 2011.
[32] See for example, Presidential Commission for the Study of Bioethical Issues, “New Directions,” 2010. The fact that “Obama knows about iGEM!” was announced by Randy Rettberg at the start of the 2011 World Final and received much applause.

iGEM might use biological materials as a substrate, but the competition is framed largely in engineering terms. Students are tasked with using genetic ‘parts’ to construct higher-order ‘devices’ and ‘systems,’ with an explicit analogy made to the abstraction hierarchies used in assembling computer networks out of basic circuit board components.[33] When introducing key concepts to the iGEM students (and synthetic biologists more generally), examples are drawn rather indiscriminately from a range of engineering disciplines, including aeronautical, mechanical, and software engineering. For example, students are encouraged to think of discrete DNA sequences as similar to electrical circuit components. The term ‘chassis’ is borrowed from mechanical engineering to describe the cellular context into which biological parts can be inserted, and that ‘drives’ gene expression. Such analogies render biological systems in engineering terms, and do allow a group of students unfamiliar with the details of genetic processes to orient themselves with a common language and begin thinking collectively. But these analogies also encounter limits in their applicability to biological systems, and must be integrated with a more biological understanding of gene expression and regulation if the students are not only to design on paper, but also build and test their genetic devices.

The target participants for iGEM have typically not yet developed strong identities grounded in their respective disciplines of study; for most, iGEM is their first experience of research. Its organizers note that the competition is a highly motivating and effective teaching method.[34] iGEM is not a straightforward pedagogical exercise, however. It is not structured along the lines of a formal taught course, but is a laboratory-based and largely student-led project that often involves scant supervisory oversight. Teams are highly interdisciplinary, comprising biologists, engineers and computer scientists, and occasionally even social scientists and designers. As we turn to the experiences of iGEM teams, we can identify ways in which these disciplines come together in the making of a synthetic biology project. In what follows, we look at how engineering and biological approaches to standards, design, intellectual property, and understandings of the social are negotiated in practice through the iGEM competition. These observations serve to complicate the nature of the relationship between engineering and biology in the development of synthetic biology, and together help to characterize what we suggest is an emergent moral economy for this group of practitioners.[35]

Standards

In advancing their case for applying engineering tools and practices to biology, engineers entering the field of synthetic biology often describe molecular biology as an *ad hoc*, craft-like practice requiring extensive expertise. This stands in contrast to how experienced molecular biologists typically discuss their activities, referring instead to a variety of well-understood or ‘standard’ tools, protocols and kits for performing the

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[33] Andrianantoandro et al, “Synthetic Biology,” 2006.
[34] Bennett, “What is iGEM?” 2010.
[35] See also Kelty, “Not an Article,” 2012.

recombinant DNA work involved in genetic engineering.[36] The engineers who developed the initial framing and agenda for synthetic biology expressed a particular wish to standardize or codify what they saw as the tacit knowledge required for recombinant DNA work, in the hope of designing interesting biological functions without having to worry about the details of DNA assembly (in other words, decoupling design practices from the fabrication of biological circuitry).[37] Examples of their early attempts to do this include the development of design standards for BioBrick biological parts, and standardized methods for assembling these parts.[38]

These initial standardization efforts have been made central to the structure and rules of the iGEM competition. At the start of the summer, teams are sent a library of standardized genetic parts (BioBricks) that they are expected to use as the basis for developing a genetic circuit or device of their own design. A core requirement of the competition is that each team must make and characterize one or more new standard biological parts to submit to the open-access Registry of Standard Biological Parts. Over 6000 BioBrick parts have so far been deposited in the Registry through the iGEM competition — in this way, iGEM is contributing to the development of a material infrastructure for synthetic biology. Teams that do not generate new standardized parts are not rewarded with medals or prizes, a rule that reinforces particular norms of sharing and community-building. As one iGEM team advisor remarked in an email upon returning from the 2008 iGEM Jamboree:

> …the main emphasis is on producing well characterized parts and posting the documentation in the Registry — hence [universities A and B], who did remarkable projects in stem cells and neurons, failed to obtain even bronze medals as they did not submit parts in standard formats that others could use.[39]

As well as highlighting the competition requirement to contribute to the repository of standardized biological parts, this email excerpt identifies one of the factors complicating attempts to push for common standards: the use of different cell types and model systems for biological engineering. As the number of model systems used by the synthetic biology community increases, the possibility of adopting common BioBrick design and assembly standards is being challenged.[40]

In practice, standards and standardization do not routinely surface as topics of explicit discussion or negotiation within iGEM teams, but they exert a great deal of influence on the summer projects. Teams are requested to conform to the standards set out in the competition rules, and most do; in this way, their choice of model organism and research questions are shaped by the competition guidelines. But sometimes the biology of the system a team chooses to work with cannot easily be made to comply with the

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[36] For example, Jordan and Lynch, "Dissemination, Standardization and Routinization," 1998.
[37] Endy, "Foundations for Engineering Biology," 2005.
[38] Knight et al, "Idempotent Vector Design," 2003; Gibson et al, "Enzymatic Assembly," 2009.
[39] Email to E. Frow dated 12 November 2008.
[40] Frow, "Big Promises," under review.

standards prescribed in the competition rules. To deviate from using standard parts and assembly methods, teams must apply for an exemption and state their reasons for choosing to pursue a different approach. If the exemption is granted, they are typically requested to submit a written document detailing the alternative standard(s) they propose to use. To date, nearly 25% of the contributions to the standard-setting process set up by the synthetic biology community have come from iGEM teams.[41] In this way, we might say that as well as contributing to the development of toolkits of biological parts, the iGEM competition is also promoting innovation in standards development for the field; these activities seem to be in tune with the engineering ethos of synthetic biology.

However, the issue of standards brings into relief a tension regarding the relative prioritization of biology and engineering: is success in the iGEM competition weighted towards the development of an engineering toolbox of parts that others can use, or is it more about the quality of the biology underpinning the project idea? While the competition rules suggest that making new BioBrick parts is central to reward at iGEM, developing a project of biological merit and relevance is also very important according to iGEM judges. Balancing these requirements typically involves some iteration between the biological and engineering elements of the project, as we discuss below.

Design in the iGEM Competition

Although iGEM is presented as an engineering-driven competition grounded in ideas of intentional design, construction, and testing, for practical purposes most teams are based in biology laboratories. Furthermore, the scope of their projects depends to some extent on the particular expertise and equipment of the lab's principal investigator. How the engineering and biological dimensions of the competition get negotiated over the summer plays out differently for each individual team (based on team composition, research experience, choice of project, etc.), but some general trends can be discerned. Engineering design ideas tend to feature strongly in the early stages of the project, as students are challenged to come up with possible projects given a toolkit of standard biological parts and basic principles of genetic circuit design. But the choice of a project and the specificities of its design also depend critically on its viability from a biological perspective. Ethnographic observations suggest that deference to the expertise of the biologists on the team and the opinions of advisors with biological knowledge is common when trying to develop and refine a project idea.[42] The first few weeks of project development typically involve cycling between (1) brainstorming ideas that are interesting as biological applications, and (2) identifying whether they might be reverse-engineered into a simple biological circuit containing a small number of standard biological parts. At this stage, iGEM seems to be more about reverse-engineering than bottom-up engineering.

Developing a design for a (simple) genetic circuit containing a defined number of standard biological parts often leads the students to think the execution of their project will be a straightforward affair. In practice, many teams face a period of disillusionment over the summer, as the building and testing of their genetic constructs almost invariably

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[41] See BioBricks Foundation, "Technical Standards Framework," 2013.
[42] Gibson, "I'd Like to Warn You," 2011.

turns out to be more challenging than anticipated.[43] Wet-lab work is usually the rate-limiting part of the project, and the 10-week timeline rarely permits a team to build their complete genetic construct, let alone test it or modify the design (as completing the full engineering design cycle would require). BioBrick assembly is presented to iGEM teams as a standardized and efficient procedure, but in practice it is often a lengthy and challenging task. Not only do the students have to learn and master laboratory protocols, but the quality control of BioBrick parts coming from the Registry can be poor, meaning that teams may have to troubleshoot or 'fix' parts that are 'broken' or do not work as predicted.[44] Based on our observations and discussions with other iGEM team advisors, the division of labour within an iGEM team often sees the biologists spending long days doing practical work in the laboratory, while the engineers and computer scientists (and any students bringing other disciplinary perspectives to the team) work in more traditional office or common-room environments on the modelling and Human Practices dimensions of the project, and on developing the project infrastructure (wiki, poster, team logo, t-shirts, etc.).

The rhetoric of engineering that frames the iGEM competition often fades into the background as iGEM teams get on with the work of their projects. Berden[45] distinguishes idealized genetic engineering principles (such as rational design, decoupling, modularization, and standardization) from more 'pragmatic' engineering principles like tinkering,[46] bricolage,[47] and kludging,[48] which may all be more appropriate ways of understanding the current practice of synthetic biology. At this stage, synthetic biology has not developed the foundational design principles necessary for the reliable design of genetic circuits;[49] much of the work both in the iGEM competition and in synthetic biology more broadly is focused on troubleshooting, simple parameter variation, and the generation of data from which more formal design principles might eventually be abstracted.[50]

In practice, engineering rhetoric typically resurfaces as iGEM teams start preparing their project presentations and posters according to the framing of the competition. The messy and often inconclusive laboratory work they engage in over the summer gets re-packaged into a clear story about the engineering of a genetic machine. iGEM presentations at the Jamboree are incredibly slick and professional, and they serve to perform and reinforce the engineering dimensions of the competition. Compared with academic presentations at scientific conferences, the details of the laboratory work that has been done by iGEM teams has a (worrying) tendency to be marginalized in the telling of a bigger and more consistent engineering story. What the students have actually

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[43] iGEM teams do often achieve a remarkable amount in a short period of time, but the projects they present rarely provide more than the most basic proof-of-principle for a more ambitious idea.
[44] Brown, "The iGEM Competition," 2007.
[45] Berden, "Designing the Discipline," 2011.
[46] Jacob, "Evolution and Tinkering," 1977.
[47] Lévi-Strauss, *The Savage Mind,* 1966.
[48] O'Malley, "Making Knowledge," 2009.
[49] Kwok, "Five Hard Truths," 2010.
[50] Schyfter, "Propellers and Promoters," 2013.

achieved in terms of practical work is not always made clear, but the ‘big ideas’ and engineering or design innovations are emphasized instead. In the public performance of iGEM (when — and perhaps because — there are prizes at stake), we see a strong projection of engineering design and rhetoric, even if the daily, messy work of iGEM teams is more grounded in tinkering with the biological systems they are trying to engineer.

Intellectual Property

In parts-based approaches to synthetic biology there has been an explicit attempt to develop a model for intellectual property protection inspired by open source software.[51] Although engineers use a range of intellectual property protection models, including patents, trademarks, copyright, registered design and trade secrets, here we see the influence of a particular type of engineering — software engineering — on the framing of synthetic biology.[52] The aspiration is that DNA sequences or biological parts could be combined in a similar way to the assembly of modular blocks of software code in computer programming.[53] The reality of developing an ‘open-source biology’ has proven difficult, however, because open source is based on copyright, while in biotechnology the dominant ownership regime since the 1980s has been one of patenting biological materials.

Efforts are currently being directed towards developing a *sui generis* ownership regime that involves signing an agreement not to assert property rights on BioBricks.[54] The motivation behind this endeavour is to facilitate a particular set of normative conventions regarding access to and sharing of biological parts. In line with this agenda, iGEM is set up as an open-access initiative. As Rettberg puts it, “The philosophy of iGEM is a philosophy of get and give. They get the parts at the beginning of the summer. They give the parts back for the iGEM teams that follow.”[55] This ‘philosophy’ is implicitly effective in that most iGEM students depend heavily on the freely available BioBricks that have been deposited in the Registry by previous iGEM teams, and also because they must submit new parts to the Registry to qualify for medals and prizes.

Like standards, intellectual property is not a topic that teams typically grapple with actively over the course of the summer— many of them are not even aware of the intellectual property regimes shaping the work they do — but it does affect the way they share their materials. This early exposure to open-access ideals also influences their attitudes to the exchange of information and resources, although largely unreflexively. When one team announced at the 2009 competition that it had filed three patents as part of its project, boos were heard in the audience. In practice, the way forward for intellectual property in synthetic biology is far from obvious. Furthermore, it should be noted that the MIT Parts Registry does not rest on secure legal foundations, not least

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[51] Campos, “The BioBrick™ road,” 2012.

[52] Two of the founders of parts-based synthetic biology, Tom Knight and Randy Rettberg, have backgrounds in software engineering.

[53] Maurer, “Before it's too late,” 2009.

[54] See BioBricks Foundation, “The BioBrick™ Public Agreement,” 2013.

[55] Rettberg, “iGEM,” 2009, p.29.

because several of its BioBricks are already subject to existing gene patents.[56] So far, this has not led to difficulties (perhaps because iGEM has yet to deliver market-ready products), but Rettberg notes: "I worry that some patent troll will send a letter to MIT and I will be shut down."[57]

Somewhat incongruously in the context of this culture of open access and sharing, a striking visual feature of iGEM is the sponsorship logos that typically adorn team t-shirts. It is not cheap to support a team of students over the summer and provide them with lab space and materials (or to fly them to Boston to compete in the Jamboree), and many teams secure small amounts of funding or in-kind contributions from a range of public and private sponsors. A more explicit orientation towards commercialization is the initiation of a new 'Entrepreneurship division' of iGEM,[58] which ran for the first time in 2012. With developments like these it remains to be seen whether ownership regimes in synthetic biology will become increasingly aligned with trends in mainstream biotechnology or succeed in establishing a distinctive system of ownership and exchange.

Imagining the Social

A particularly interesting aspect of the competition relates to how teams engage with the social dimensions of their work. Arguably, the ways in which social dimensions of biotechnology and engineering are imagined and incorporated into practice have followed different trajectories over the past 30-40 years. In brief, an interdisciplinary academic field of 'engineering ethics' was forming by the 1980s, concerned principally with identifying real-world contexts and "situations in which engineers often find themselves and provid[ing] concepts and frameworks with which to think through these situations."[59] In the US, engineering ethics has become a required component of accredited undergraduate engineering programs since 2000.[60] The emphasis is largely on training engineers to have an understanding of their professional and ethical responsibilities in a business context. Adopting a more constructivist lens, we might say that these efforts encourage upstream integration of social concerns into engineering practice, in the hope of developing 'heterogeneous engineers'[61] or 'reflexive engineers'[62] who strive to incorporate an understanding of social, political, economic and human factors into their technical work.

In contrast, undergraduate training in biosciences typically has no such required 'ethics' or professional responsibility component. Early concerns about the potential biosafety implications of recombinant DNA technology led to attempts at self-regulation by practicing molecular biologists (as seen in the 1975 Asilomar meeting, for example), and a series of biosafety regulations and guidelines have since been established for working with and managing the release of genetically modified organisms. In parallel, a flourishing field of social science research has evolved around the broader implications of

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56 Rai, "Synthetic Biology: Innovation and Open Source," 2009.
57 Rettberg, "iGEM," 2009, p.38.
58 iGEM Entrepreneurship Division, 2012.
59 Johnson and Wetmore, "STS and Ethics," 2008, p.570.
60 ABET, "Criteria for Accrediting," 2004.
61 Law, "Heterogeneous Engineering," 1987.
62 Robbins, "The Reflexive Engineer," 2007.

the life sciences. Notably, 3-5% of the budget for the Human Genome Project was devoted to studying its ‘ethical, legal and social implications’ (ELSI),[63] and increased funding has followed from developments such as the controversies surrounding GM crops in Europe. In contrast to engineering ethics, ELSI research has not focused on the training of molecular biologists. It has also been criticised for focusing on downstream ‘implications’ of genetic research (including public acceptance) as opposed to integrating research findings into the trajectories of scientific research and development.[64]

In practice, discussions of the social dimensions of synthetic biology have so far been articulated primarily in relation to the landscape of bioscience and biotechnology research. Synthetic biologists make frequent reference to, for example, European experiences of controversies over GM crops, as well as the potential biosecurity implications of synthetic biology. The social science funding initiatives research that have been initiated for synthetic biology build on and extend practices initiated for genomics and nanotechnology. However, in an explicit attempt to distance themselves from more traditional ELSI research, anthropologist Paul Rabinow and his colleagues at the SynBERC center at Berkeley coined the term ‘Human Practices’ to describe their research efforts.[65] Their use of this term isindicative of the model of upstream integration they intended to pursue, “an approach that fosters ongoing collaboration among disciplines and perspectives from the outset.”[66] This is perhaps an ethos more closely aligned with the integrative aspirations of engineering ethics, although not concerned specifically with training students. Notably, the majority of social scientists who are currently involved in studying synthetic biology and working with synthetic biologists have a track record of studying the life sciences. To date, core issues in Human Practices work are more closely aligned with key social, legal and ethical concerns identified for molecular biology and biotechnology research than they are with the central preoccupations of engineering ethics.

Human Practices has been brought into iGEM as an optional component of the competition; it was introduced in 2008 as one of several activities a team can choose to complete in order to win a Gold medal. (In 2011, approximately 80% of the teams undertook some Human Practices work.) This explicit attention to social dimensions distinguishes iGEM from more traditional student competitions in engineering. In the context of the competition, Human Practices is conceived very broadly to apply to any non-technical aspects of the team’s project.[67] There is currently much flexibility

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[63] Department of Energy, *Ethical, Legal and Social Issues*, 2011.
[64] Fisher, “Lessons Learned,” 2005.
[65] A number of STS researchers in the UK have also organized a series of workshops in an attempt to discuss practical research agendas for synthetic biology and their theoretical and normative implications (ESRC Seminar Series on Synthetic Biology and the Social Sciences, 2013).
[66] Rabinow and Bennett, *Designing Human Practices*, 2012, p.40.
[67] The description of Human Practices provided to iGEM teams in 2008 was:

> Issues? We've got issues! How will you sell your project if you have to give away the parts? What does your family think about your genetic engineering dreams? Will the world be a safe place if we make biology easy to engineer? How do the lessons of the past inform everybody's discussion going forward? Find a new way

regarding what constitutes Human Practices, and indeed significant ambiguity (and sometimes heated contestation among iGEM judges) about what should be rewarded as 'good' Human Practices work, but it should be noted that Human Practices as currently conceived does not consist of formal training or the provision of codes of responsible conduct.[68] Furthermore, the vast majority of iGEM teams do not include students from the humanities, social sciences or design world, nor do they have advisors with social science or humanities expertise; this leaves the development of Human Practices activities largely in the hands of undergraduate engineers, biologists and computer scientists (often with the division of labour noted above).

In practice, iGEM teams approach Human Practices from a variety of perspectives, which itself might be said to reflect different imaginations of the social at play. Based on our observations and encounters with iGEM teams, it is common for Human Practices work to be conceived of and conducted as a discrete and separate component of an iGEM project, and indeed to be developed once the team's core project is well underway. This approach effectively divorces 'the social' from 'the technical,' positioning Human Practices work downstream of the research being done. Many teams adopt a standard 'deficit model' approach and devise activities to educate and enthuse members of the lay public about synthetic biology. Surveys (often of poor quality) are also frequently used to try and identify public attitudes towards synthetic biology. Such projects might be said to stem from a conception of the social largely grounded in traditional ELSI concerns of public understanding and engagement. But other projects are grounded in an imagination of the social more closely aligned with computer science ideas about playing and hacking, pursuing activities such as studies of the 'Do-It-Yourself' biology movement,[69] or discussions of how synthetic biology could be re-purposed for ordinary citizens to use.[70] Impressive examples of heterogeneous engineering can be found in the Human Practices work of Imperial College London in 2010 and 2011, where the views of potential users were incorporated into the design of the team's biological devices.[71] This type of more integrated and 'upstream' Human Practices work, in which teams undertake activities relating directly to the content of their projects and are prepared to revise their technical designs, is more consistently rewarded by the iGEM judges than most other Human Practices activities.

Thus, although iGEM is presented as an engineering competition, we might say that the presence and framing of Human Practices in iGEM and synthetic biology more generally builds on an established trajectory within bioscience research. Traditional ELSI concerns including biosafety and biosecurity are a focus of much current Human

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> to help human civilization consider, guide, and address the impacts of ongoing advances in biotechnology (iGEM Judging Criteria, 2008).

[68] This said, iGEM organizers are keen to promote the development of a community that shares values about safety, security and open access to toolkits and technologies. Teams are now required to complete a series of safety questions, and may be disqualified from the competition if they fail to do so.

[69] Peking University iGEM Team, 2009.

[70] ArtScience Bangalore iGEM Team, 2011.

[71] Imperial College iGEM Team, 2010.

Practices work.[72] Those trained in biology may be more likely to see social considerations as 'outside' their immediate sphere of work, leading them to focus on ethics, public acceptance, and 'outreach' as key Human Practices activities. But there is a growing tendency for iGEM judges to reward those teams who embrace the spirit of heterogeneous engineering and incorporate an understanding of social, political, economic and human factors into the details of their technical projects. Engineers do not typically work with biological materials as substrates, and it may be that this necessitates a broadening out of the social dimensions they engage with (for example, extending to ethical considerations regarding the creation of 'life'). A flexible space for interaction between ELSI and engineering ethics work might be starting to open up through the iGEM competition, in response to demands for training a new generation of reflexive (bio)engineers.

Conclusions

The organizers of iGEM have framed it as an engineering competition, with an emphasis on designing and making things – activities that fit comfortably into the engineer's domain. Their aim has been to use iGEM, an undergraduate competition, as proof-of-principle for a broader research and policy agenda in support of synthetic biology. In several respects, iGEM has proven phenomenally successful — in enrolling and training a community of synthetic biologists, in building shared infrastructure, and in defining research areas. But our observations of the work undertaken by iGEM teams complicate the engineering-led rhetoric and show that in practice the students have to negotiate the demands of both biology and engineering. Importantly, biology keeps surfacing and asserting itself in various ways throughout the competition: in the details of laboratory work, in resisting the application of certain standards, in being subject to existing property protection regimes for the life sciences, and in the dominant ELSI imagination of the social.

Even though the engineering rhetoric fades as iGEM teams get down to the often frustrating laboratory work demanded by their projects, we see it strongly reasserted in team presentations at the Jamboree. During their presentations, teams sometimes joke about how BioBricks do not always 'behave' as they are meant to, but overall it is as though the struggles and dissatisfactions of the laboratory work are forgotten in the excitement of the competition and the enthusiasm to win a prize. The Jamboree itself is 'marked by an affect of confidence and possibility,'[73] in which every student is encouraged to 'share your passion about synthetic biology.'[74] It is in this context that Randy Rettberg puts up a slide during the awards ceremony reminding everyone of the central question for the competition: 'Can simple biological systems be built from standardized interchangeable parts, or is biology so complex that each case is unique?' He then asks the assembled students: 'How many of you are discouraged?' — which results in silence. He follows this with: 'How many of you are excited?' — provoking

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[72] Notably, Human Practices judges in 2011 included two employees of the US Department of Defense.

[73] Bennett, "What is iGEM?" 2010, p. 4.

[74] iGEM World Championship Opening Ceremony, 2011.

loud cheers. In this way, the competition builds and reinforces the possibility of success for the parts-based approach to synthetic biology.

Public proclamations about iGEM (and synthetic biology more generally) use ‘engineering’ and ‘biology’ as key reference points. But our study of iGEM in practice reveals the importance of other disciplines that are sometimes overlooked, not least computer science. For example, the process for standard-setting in synthetic biology is explicitly modelled on that developed by the Internet Engineering Task Force,[75] and the novel intellectual property regimes being developed to encourage the sharing of biological parts have been strongly influenced by open-source software.[76] Furthermore, ideas of ‘play’ and ‘hacking’ that feature regularly in iGEM come from an imagination of the social that is grounded in computer science.[77] The situation is further complicated because computer science is sometimes used interchangeably with engineering, but on other occasions it is treated as a discipline with distinct contributions to make (for example, in the separate ‘software’ track of iGEM).[78] The role of computer science as an interface between biology and engineering is currently under-explored, and is often left out when synthetic biology is presented as a hybrid of biology and engineering (perhaps because its role is still being negotiated).

The now well-rehearsed dichotomy between science and engineering is further problematized by noting that most iGEM students have yet to adopt a firm disciplinary identity. (This being said, their contributions to the team’s project are typically determined by their training to date.) When it comes to iGEM, synthetic biology is perhaps less about a confrontation between two epistemic cultures as the opportunity to create a new space in which values, conventions, and ways of knowing and doing are being (re)defined. One way of understanding the iGEM competition is as an attempt to establish a new moral economy for biotechnology, through its efforts to structure and reward certain norms of practice, responsibility, and exchange. At this stage, the notion of moral economy seems to capture the fluidity in epistemic and institutional systems that currently characterizes iGEM more aptly than focusing on the more reified concept of epistemic cultures.

By studying iGEM in practice, we show how the relationships between biology, engineering and other disciplines are complicated in ways that are notably distinct from the rhetorical framing of the competition and synthetic biology more broadly. How might engineering studies contribute to the study of this multi-disciplinary site? In general terms, as engineers (and physicists and mathematicians) become more involved in biology, it is clear that insights from engineering studies will become increasingly

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[75] Frow, “Big Promises,” under review.
[76] Calvert, “Ownership and Sharing,” 2012.
[77] An example of a confusion of different imaginations of the social is seen in the report of the US Presidential Commission for the Study of Bioethical Issues, “New Directions,” 2010, where ‘playing God’ (associated strongly with genetic modification and the biological imagination of the social) is linked to notions of ‘play’ found in the DIYBio community (the computer science imagination of the social). It is argued that instead of ‘play’ a culture of ‘responsibility’ should be introduced (pp.147-8).
[78] iGEM Software, 2012.

relevant.[79] More specifically, we see the notion of heterogeneous (bio)engineering as being a fruitful entry point for bringing together engineering studies and social studies of the life sciences. For example, in addressing how iGEM teams imagine the social in their Human Practices work, we see how rather narrow ELSI understandings of the 'downstream' implications and public acceptance of synthetic biology dominate. We believe that the activities of iGEM teams could be enriched by insights from more 'upstream' engineering ethics education, and that in turn the remit of engineering studies could be extended to engage with issues raised specifically by the challenge of working with biological substrates. iGEM is an intriguing pedagogical space that is proving to be influential in the growth of a new field. It provides a rich site not only for fieldwork and academic study, but also to influence the development of a future generation of synthetic biologists.

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